Executive Summary

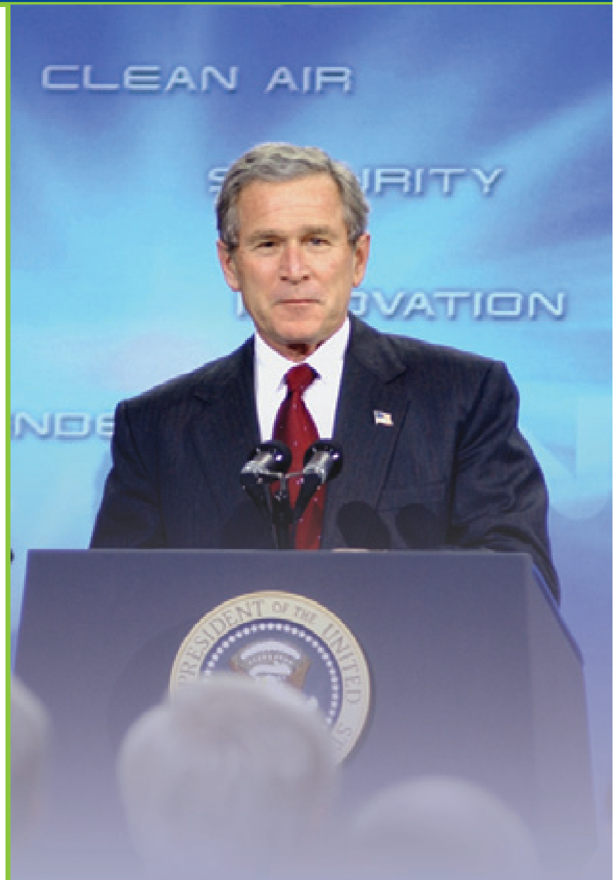
President Bush launched the Hydrogen Fuel Initiative to ensure our nation's energy security and environmental viability. Using hydrogen to fuel our economy can reduce U.S. dependence on imported petroleum, diversify energy sources, and reduce pollution and greenhouse gas emissions. Fuel cells are an important enabling technology for a future hydrogen economy and have the potential to revolutionize the way we power our nation, offering cleaner, more-efficient alternatives to today's technology.

Energy Security: The U.S. uses about 20 million barrels of oil per day, at a cost of about $2 billion a week. Much of this oil is used to power highway vehicles. Because hydrogen can be derived from a variety of domestically available primary sources, including fossil fuels, renewable resources, and nuclear power, its use would allow us to diversify our energy supply and make us less reliant upon foreign energy sources.

Environmental Benefits: Hydrogen generation and carbon-management technologies can be developed which can significantly reduce pollutants and greenhouse gases from fossil-based hydrogen production. Using renewable or nuclear-based hydrogen in high-efficiency fuel cells to fuel our vehicles and to generate power could virtually eliminate greenhouse gas emissions. In addition, fuel cells powered by pure hydrogen emit no harmful pollutants.

Improved Energy Efficiency: Fuel cells are significantly more energy efficient than combustion-based power generation technologies. Internal-combustion engines in today's automobiles convert less than 30 percent of the energy in gasoline into engine power for moving the vehicle. Vehicles using electric motors powered by hydrogen fuel cells are much more energy efficient, utilizing 40 to 60 percent of the fuel's energy.

Economic Competitiveness: Heavy dependence on imported oil threatens America's economic well-being. Small changes in the price of crude oil or



"With a new national commitment, ... the first car driven by a child born today could be powered by hydrogen, and pollution-free."

–President Bush

By 2040, with 150 million hydrogen powered light-duty cars and trucks on the road, hydrogen and fuel cells could reduce oil use by 11 million barrels a day—a significant reduction considering America currently imports between 10 and 11 million barrels of oil each day. We would also reduce our use of petroleum by a third and our carbon dioxide emissions by 19 percent.

disruptions to oil supplies can have big impacts on our economy, from trade deficits, to industrial investment, to employment levels. Hydrogen's diversity in production and flexibility in use offers opportunities for new players in energy markets, broadening our energy choices and increasing economic growth both at home and around the world. For example, developing and leading the way in hydrogen fuel cell technologies for automobiles will help the U.S. to maintain its future economic competitiveness in the worldwide automotive industry.

Path Forward: Addressing Barriers to a Hydrogen Economy

The transition of our current energy infrastructure to a clean and secure energy infrastructure based on hydrogen won't happen overnight. The technology, economic, and institutional barriers pose difficult challenges. The "critical path" barriers to a hydrogen economy are:

Technology Barriers

- Hydrogen storage systems for vehicles are inadequate to meet customer driving range expectations without intrusion into vehicle cargo or passenger space.
- Hydrogen is currently three to four times as expensive as gasoline.
- Fuel cells are ten times more expensive than internal combustion engines and do not maintain performance over the full useful life of the vehicle.

Economic and Institutional Barriers

- Investment risk of developing a hydrogen delivery infrastructure is too great, given technology status and current demand.
- Uniform model codes and standards to ensure safety, insurability, and fair global competition are lacking.
- Local code officials, policy makers, and the general public lack education regarding hydrogen safety and benefits.

Defining Success and Measuring Progress

Success for the Hydrogen, Fuel Cells & Infrastructure Technologies Program is defined as validation, by 2015, of technology for:

- Hydrogen storage systems enabling minimum 300-mile vehicle range while meeting identified packaging, cost, and performance requirements.
- Hydrogen production to safely and efficiently deliver hydrogen to consumers at prices competitive with gasoline without adverse environmental impacts.
- Fuel cells to enable engine costs of less than $50/kW (in high volume production) while meeting performance and durability requirements.

If these indicators are met, there is a high probability of success that customer requirements can be met, and that industry will begin to realize a business case for proceeding with a positive commercialization decision regarding hydrogen infrastructure and fuel cell vehicles.

A management approach that includes systems integration and analysis functions, along with configuration control on cost, schedule, and technology requirements will ensure that informed decisions are made and accountability is maintained.

To assist in measuring interim progress towards the 2015 commercialization decision, the following program milestones have been established with industry input, and will be monitored by the Office of Management and Budget within the Executive Office of the President:

Hydrogen Production

- Reduce cost hydrogen production from natural gas or liquid fuels at a price equivalent to $1.50 per gallon of gas at the pump by 2010 from the current price equivalent of $5.00 per gallon.
- Develop and demonstrate hydrogen production from biomass at $2.60 per kilogram by 2010 and competitive with gasoline by 2015, from the current cost of $3.60-$3.80 per kilogram.
- By 2015, demonstrate hydrogen production by direct water-splitting at a plant gate cost of $5.00

In his concluding remarks to the National Hydrogen Energy Roadmap Workshop participants (April 2-3, 2002, Washington, DC), David Garman, Assistant Secretary for Energy Efficiency and Renewable Energy, stated:

"There are two paths we need to follow: research and development, and public outreach to capture the imagination of the American people. This will be a long journey and process, and the Department of Energy will work with you as we move forward."

"As we go forward into the 21st century, we will see a huge explosion in demand for energy, both here at home and around the globe, especially the developing world. Failing to meet that demand threatens our nation's energy and economic security. The United States today obtains 54 percent of its oil from foreign sources. That dependency is projected to grow to 68 percent by 2025."

Secretary of Energy, Spencer Abraham, 14th National Hydrogen Association Annual Conference, March 5, 2003

per kilogram photoelectrolytically and $10 per kilogram photobiologically, from a current cost of more than $200 per kilogram.
- By 2010, verify large-scale central electrolysis at $2.00 per kilogram of hydrogen from the current $2.60 per kilogram.

Hydrogen Delivery

- By 2010, reduce cost of hydrogen fuel delivery from central production to refueling station to less than $0.70 per kilogram and the cost of on-site movement and handling to less than $0.60 per kilogram, and by 2015, have a combined cost of below $1.00 per kilogram.

Hydrogen Storage

- Demonstrate on-board hydrogen storage systems with a 6% capacity by weight by 2010 and a 9% capacity by 2015.

Fuel Cells

- Develop polymer electrolyte membrane automotive fuel cells that cost $45 per kilowatt by 2010 and $30 per kilowatt by 2015, from the current $200 per kilowatt.
- Develop a distributed generation PEM fuel cell system with 40% electrical efficiency and 40,000 hours durability at $750 per kilowatt by 2010, from the current 30% efficiency and 20,000 hours durability at $15,000 per kilowatt.

Technology Validation

- Validate an integrated biomass/wind or geothermal electrolyzer-to-hydrogen system for $3.30/kg at the plant gate by 2010.

Codes and Standards

- Complete U.S. adoption of a Global Technical Regulation for hydrogen fuel cell vehicles by 2010.

Safety

- By 2010, publish a handbook of Best Management Practices for Safety that will provide guidance for ensuring safety in future hydrogen endeavors.

Education

- Launch a comprehensive and coordinated public education campaign about the hydrogen economy and fuel cell technologies by 2010.

DOE has identified the key program milestones necessary to meet these technical targets (Figure I). These milestones support the critical path technologies outlined by DOE. Each of the timelines specify a delivery date for the given technology development, improvement, or demonstration. As technologies evolve and economic and systems analyses data become available, these targets will be refined. The go/no-go decision milestones are also identified in Figure I. At these decision points, DOE will evaluate each technology approach under development. If DOE determines that a particular approach cannot meet the program goals and objectives, it will be dropped from the technology portfolio and program resources will be refocused on the approaches that have the most potential to meet the goals and objectives of the Hydrogen, Fuel Cells & Infrastructure Technologies Program.

Educating consumers, industry leaders, and public policy makers about the benefits of hydrogen is critical to achieving the vision.

A domestic hydrogen energy system will help DOE's EERE meet four strategic goals.

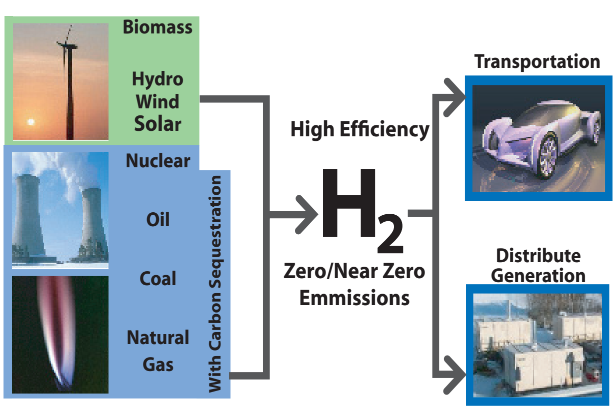
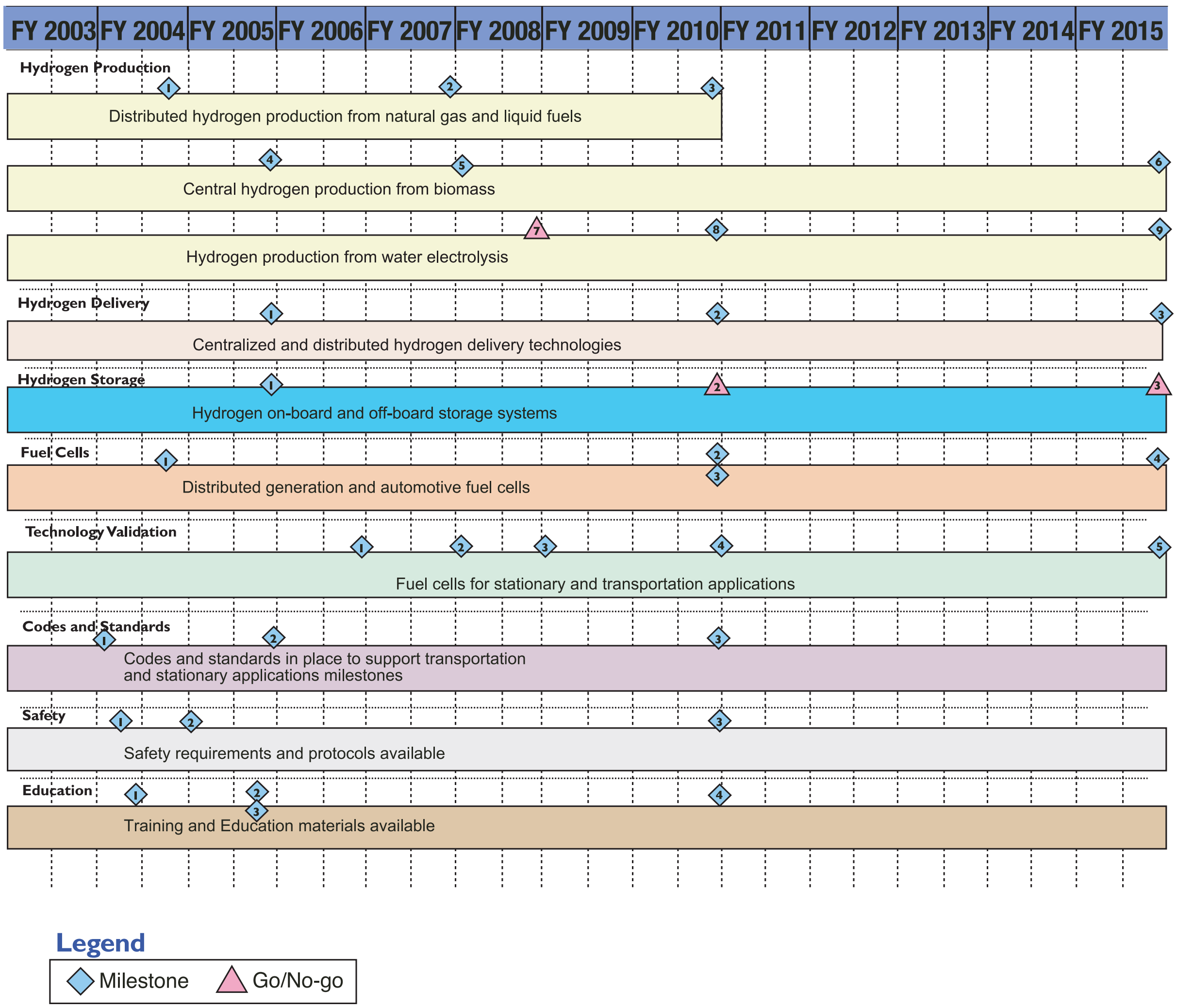


Figure I. Rollup of Key Sub-Program Milestones



For chart details see next page.

1. Develop hydrogen production technologies for distributed systems using natural gas and liquid fuels with a projected cost of $3.00/kg hydrogen at the pump. (Milestone #3 in Table B.1)
2. Develop hydrogen production technologies for distributed systems using natural gas or liquid fuels with a projected cost of $2.50/kg hydrogen at the pump. (Milestone #6 in Table B.1)
3. Develop hydrogen production technologies for distributed systems using natural gas or liquid fuels with a projected cost of $1.50/kg hydrogen at the pump. (Milestone #7 in Table B.1)
4. Select and develop biomass gasification technologies to reduce hydrogen cost to $3.30/kg. (Milestone #12 in Table B.1)
5. Verify biomass-based production of hydrogen at projected cost of $2.60/kg at the plant gate. (Milestone #17)
6. Verify biomass-based production of hydrogen at a cost that is competitive with gasoline. (Objective, Section 3.1)
7. Go/No-Go: Identify semiconductor materials that can achieve >10% solar-to-hydrogen efficiency, with projected durability of 10,000 hours, with a cost approaching $22/kg. (Milestone #32 in Table B.1)
8. Verify renewable integrated hydrogen production with water electrolysis at a hydrogen cost of $2.50/kg. (Milestone #38 in Table B.1)
9. Demonstrate an engineering-scale biological system that produces hydrogen at a plant-gate cost of $10/kg projected to commercial scale and direct photoelectrochemical water splitting with a plant-gate hydrogen production cost of $5/kg projected to commercial scale. (Objectives, Section 3.1)

1. Complete definition of a cost-effective hydrogen fuel delivery infrastructure for the introduction and long-term use of hydrogen for transportation and stationary power. (Milestone #1 in Table B.2)
2. Develop enabling technologies to reduce the cost of hydrogen fuel delivery from central/semi-central production facilities to the gate of refueling stations to <$0.70/kg and cost of hydrogen movement and handling within the refueling stations and stationary power facilities to <$0.60/kg (Objectives, Section 3.2, and Milestones #7 and #11 in Table B.2)
3. Develop enabling technologies to reduce the cost of hydrogen fuel delivery from the point of production to the point of us in vehicles or stationary power units to <$1.00/kg in total. (Objective, Section 3.2)

1. Develop and verify on-board hydrogen storage systems achieving 1.5 kWh/kg (4.5 wt%), 1.2 kWh/L and $6/kWh. (Objective, Section 3.3)
2. Develop and verify on-board hydrogen storage systems achieving 2 kWh/kg (6 wt%), 1.5 kWh/L and $4/kWh. (Objective, Section 3.3)
3. Develop and verify on-board hydrogen storage systems achieving 3 kWh/kg (9 wt%), 2.7 kWh/L and $2/kWh; vehicle interface technologies for fueling on-board hydrogen storage systems; and low-cost, off-board hydrogen storage systems. (Objective, Section 3.3)

1. Go/No-Go: Downselect technology to meet year 2010 technical target (80% efficiency, 800 W/L, 800 W/kg, < 0.5 minute start-up). (Milestone #25 in Table B.4)
2. Develop a distributed generation PEM fuel cell system that achieves 40% electrical efficiency and 40,000 hours durability at $400-750/kW
3. Develop a 60% efficient, durable, direct hydrogen fuel cell power system for transportation at a cost of $45/kW. (Objective #1, Section 3.4)
4. Develop a 60% efficient, durable, direct hydrogen fuel cell power system for transportation at a cost of $30/kW. (Objective #1, Section 3.4)

1. Five stations and maintenance facilities constructed with advanced sensor systems and operation procedures. (Milestone #27 in Table B.5)
2. First regional networks with fuel cell systems that project < $1,250/kW. (Milestone #36 in Table B.5)
3. Demonstrate fuel cell vehicles with 300-mile range and 2,000 hours of fuel cell system durability. (Milestone #20 in Table B.5)
4. Validate $3.30/kg hydrogen cost from biomass/wind. (Milestone #43 in Table B.5)
5. Direct hydrogen PEM fuel cell vehicles demonstrated, achieving 300+ mile range and 5,000 hours fuel cell system durability to enable commercialization decision.

1. With industry and code officials, develop templates of commercially viable footprints for fueling stations that incorporate underground and above ground storage of liquid and gaseous hydrogen. (Milestone #24 in Table B.6)
2. Implement analytical and experimental program to support the submittal of a comprehensive vehicular safety standard as a regulation. (Milestone #30 in Table B.6)
3. Codes and Standards in place to support transportation and stationary applications. (Goal, Section 3.6)

1. Develop safety requirements and protocols for bulk hydrogen and on-board storage. (Milestones #4 and #5 in Table B.7)
2. Develop safety requirements and protocols for vehicle safety and stationary refueling. (Milestone #11 in Table B.7)
3. Final Best Management Practices Handbook completed. (Milestone #55 in Table B.7)

1. Establish educational materials library and information clearinghouse/distribution system to serve the immediate needs of multiple audiences. (Milestone #4 in Table B.8)
2. Publish codes and standards modules and safety training materials. (Milestones #7 and #8 in Table B.8)
3. Launch coordinated materials development and teacher training/professional development program for secondary school teachers. (Milestone #18 in Table B.8)
4. Launch a comprehensive and coordinated public education campaign about the hydrogen economy and fuel cell technology. (Objectives, Section 3.8)

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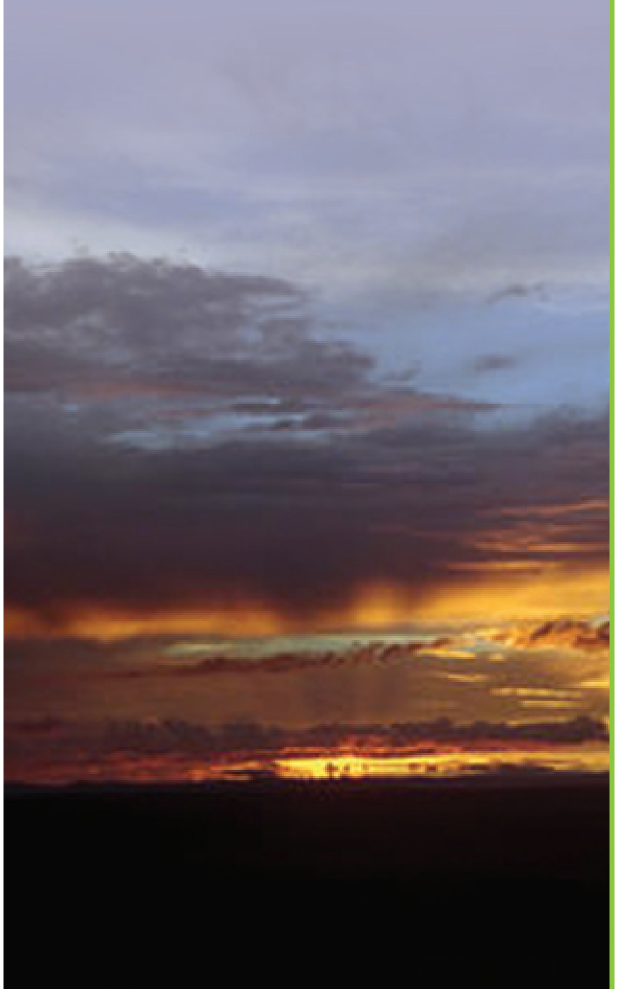
it's important for our country to understand that by being bold and innovative, we can change the way we do business here in America; we can change our dependence upon foreign sources of energy; we can help with the quality of the air; we can make a fundamental difference for the future of our children.

–President Bush
Hydrogen Fuel Initiative Can Make "Fundamental Difference"



Achieving Success

Putting it all together is the ultimate challenge. To achieve the goal of commercially-viable hydrogen and fuel cell systems in the 2015 timeframe:

- R&D efforts must be focused on the most promising technologies, and
- Customer requirements must be validated in a fully-integrated operating system.

The Hydrogen, Fuel Cells & Infrastructure Technologies Program is emphasizing a results-driven management approach, in accordance with the principles laid out in the President's Management Agenda, to ensure that efforts are continually refocused on technologies that are most likely to achieve the goals of the Program. The technical targets provide clear quantifiable measures, which can be used to track progress and to show the return on investment of taxpayer dollars. Periodic milestones and go/no-go decision points ensure that funds will be used only for the most promising technology approaches and that performance goals are being met along the way.

The technological advancements in each program element and lessons learned from successful demonstrations of hydrogen and fuel cell technologies must be integrated to work together as a fully functional system. This is the focus of systems integration--understanding the complex interactions between components, systems costs, environmental impacts, societal impacts and system trade-offs. Identifying and analyzing these interactions will enable evaluation of alternative concepts and pathways, and result in well-integrated and optimized hydrogen and fuel cell systems.

As we look to the future, hydrogen and fuel cell technologies promise to meet an ever-growing portion of our nation's energy needs. The U.S. Department of Energy is building partnerships between national laboratories, universities, and industry to speed up the development of hydrogen technologies. Together, we will realize our vision of a hydrogen energy future.